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Benchmarking Carbon Emissions Performance in Supply Chains

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Benchmarking Carbon Emissions Performance in Supply Chains

Structured Abstract:

Purpose

Benchmarking has become an important issue in supply chain management practice. However, challenges such as supply chain complexity and visibility, geographical differences, non-standardized data have limited the development of approaches for evaluating performances of product supply chains. The paper aims to develop a benchmarking framework to address these issues ensuring that the entire supply chain environmental impact (in terms of carbon) and resource use for all tiers, including domestic and import flows, are evaluated. This industry-level benchmarking approach ensures that individual firms can compare their carbon emissions against other similarly structured firms.

Design/Methodology/Approach

The benchmarking framework utilises the Multi-Regional Input-Output methodology to develop product supply chain carbon maps on which industry-level benchmarks are based. The steel industry supply chain is used to demonstrate the application. Carbon emissions and resource requirements are chosen as environmental sustainability indicators.

Findings

Supply chain carbon maps are developed as a means of producing industry-level benchmarks to set a measure for the environmental sustainability of product supply chains. The industry-level benchmark provides the first step for firms to manage environmental performance, identify and target high carbon emission hot-spots and for cross-sectoral benchmarking.

Originality/value

The paper links the theoretical development of supply chain environmental systems, based on the Multi-Regional Input-Output model, to the innovative development of supply chain carbon maps; such that an industry-level benchmarking framework is produced as a means of setting product supply chain carbon emissions benchmarks.

Keywords: Industry-Level Benchmarking, Carbon Maps, Green Supply Chain Management, Input-Output, LCA, Environmental Performance Measurement

1 Introduction

Because of the close linkage and impacts of economic systems on the environment (Schaltegger and Synnestvedt 2002), issues related to business sustainability have taken root in supply chain management practices. This can also be attributed to the fact that besides the competitive advantage these can offer to businesses, companies are nowadays held accountable for their environmental performance by three key stakeholders groups, namely: organisational stakeholders (suppliers and partners, employees, management, etc), societal stakeholders (media, consumers and community and interest groups, etc) and regulatory bodies (stakeholders that set laws or lobby government to set laws).

In order to make the transition towards sustainable supply chains, decision making in organisations needs to be informed by supply chain sustainability research (Burritt *et al.,* 2002). This is because recent studies have clearly interconnected supply chain strategies and their environmental consequences (Handfield *et al.,* 2005 and Paulraj 2009) and in particular how this can form the basis for sustainable supply chain performance management (Hervani *et al*., 2005). In this context, benchmarking approaches may be a useful technique for identifying improvement opportunities in supply chains (Beamon 1999) and, therefore, favouring the transition towards sustainable supply chains.

Generally, business sustainability requires companies to develop and adopt economically, environmentally and socially sustainable practices (Schaltegger *et al*., 2008). In terms of environmental sustainability, because of the environmental impacts created along product supply chains, management strategies are increasingly including prescriptions about supply chain lifecycle assessments (Acquaye *et al*., 2011 and Koh *et al*., 2013) and their implications for decarbonisation and mitigation efforts (Weber and Peters, 2009; Confederation of British Industry, 2011 and Koh *et al*., 2013). Indeed, the integration of life cycle analysis principles at the supply chain design phase maximizes long-term sustainability (Chaabane *et al*., 2012). However, supply chains are inherently complex because of the globalized nature of multi-tier process and service inputs. Hence, in order to satisfy a key principle underlining sustainable supply chains (that is, visibility of the entire upstream and downstream supply chains) (Carter and Rogers, 2008 and Carter and Easton, 2011), any environmental sustainability assessment methodology utilised to inform performance measurement and benchmarking must address this complexity. A review of supply chain benchmarking literature suggests this is clearly lacking (Beamon 1999; Gunasekaran *et al.*, 2001; Hervani *et al.*, 2005).

Informed by the principles of lifecycle assessments, supply chain maps can formally and visually represent the interaction between different entities within a supply chain. According to Gardner and Cooper (2003) and Acquaye *et al.* (2012) supply chain mapping offers businesses a range of benefits including the identification of areas where inefficiencies can be improved and a support in supply chain redesign or modification. As an extension to these benefits offered by supply chain maps and to address the gaps in knowledge deriving from the inherent complexity of product supply chains and from challenges in supply chain performance measurement and benchmarking (Beamon 1999; Gunasekaran *et al.*, 2001 and Hervani *et al.*, 2005), the following research questions are addressed in the paper:

i. Based on the multi-regional input-output analysis approach, how can a carbon assessment methodology be applied to product supply chains for developing a benchmarking framework which ensures that the entire supply chain impacts (in terms of carbon) and resource use for all tiers of the supply chain, including domestic and import flows are evaluated?

ii. By designing and developing product supply chain maps based on carbon emissions and resource requirements, how can these maps form the basis for industry-level benchmarking against which individual firms can compare their carbon emissions performance against other similarly structured firms?

Based on these research questions, the paper presents a systematic approach for designing and developing supply chain maps which can be used as a benchmark for environmental sustainability (in terms of carbon) in performance measurement of product supply chains. This would be undertaken by using relative resource requirements and carbon emissions as environmental indicators. As such, by gaining insight into the visibility of product supply chains (such as relative resource requirements for all tiers of the supply chain, including domestic and import flows), their environmental sustainability can be benchmarked and greener operations opportunities adopted. As Faruk *et al.* (2001) noted, by understanding the entire (upstream and downstream) supply chain impacts, better strategic actions can be taken; furthermore, these actions may have a much wider positive impact. This benchmarking process can also serve as a useful means of supporting companies in the successful operationalization and implementation of their carbon management strategy using carbon accounting (Schaltegger and Csutora, 2012).

The supply chain maps developed and presented in this paper are based on the Multi-Regional Input-Output (MRIO) methodology which takes a system-wide perspective (details are presented in Section 3). Approaches to design, evaluate and benchmark the performance of product supply chains based on relative resource requirements, and emissions profiles are illustrated. To test the applicability of using supply chain maps as an industry benchmark, a case-study from the UK steel industry is utilised.

By identifying the supply chain paths that drive resources requirements and life cycle carbon emissions, supply chain managers and decision-makers are provided with the information to benchmark their supply chain performance, by identifying the critical hot-spots which must be targeted in order to efficiently reduce the carbon emissions. This view is supported by Busch and Hoffmann (2011) who stated that when carbon emissions are used as an outcome-based measurement, corporate environmental performance pays off. By adopting a system wide supply chain perspective in this study, a major opportunity for comprehensive supply chain performance measurement through benchmarking at the industry level is therefore presented. At the same time the system perspective increases the pressure on companies along the supply chain to adopt environmentally responsible business practices to green their entire supply chains (Srivastava, 2007 and Abdallah *et al.*, 2012).

The paper will be structured as follows: In Section 2, a literature review of supply chain performance measurement and supply chain mapping will be undertaken to provide context. This paper adopts a macro-economic supply chain modelling approach based on the principles of lifecycle assessments to develop supply chain maps and provide a basis to manage and benchmark supply chain performance. Details of the general methodology and theoretical underpinning are provided in Section 3. Section 4 illustrates the development of supply chain maps. The results of the study are presented and discussed in Section 5 allowing for conclusions to be drawn in Section 6.

2 Literature Review

2.1 Supply Chain Performance Measurement and Benchmarking

Following Neely *et al's* (1995) definition of performance measurement and various literature reviews (*inter alia:* (Beamon, 1999; Chan, 2003; Hervani *et al.*, 2005; Ritchie and Brindley, 2007 and Schaltegger, 2011)), supply chain performance measurement has generally dealt with a systematic way of quantifying the effectiveness and efficiency of the supply chain using appropriate quantitative or qualitative methods. Such supply chain performance measurement includes benchmarking approaches which provide a useful way to identify improvement opportunities (Beamon, 1999) and in strategic, tactical and operational planning capable of shaping objectives, actions and decisions (Gunasekaran *et al.*, 2004). Supply chain performance measurement can be undertaken from the perspective of the focal firm (Hubbard, 2009) or from the perspective of different stakeholders in the supply chain such as manufacturing (Jain *et al.*, 2011), distribution and logistics (Keebler and Plank, 2009) and consumers (Zhao *et al.*, 2001). In recent times, there has been a growing interest in measuring sustainability performance of supply chains which has resulted in the emergence of green supply chain performance measurement frameworks (Bai *et al.*, 2012; Björklund *et al.*, 2012, Genovese *et al.*, 2013a). In terms of environmental sustainability, such performance measurement is based on the principle of lifecycle assessment (Sarkis, 2012) which is usually employed to evaluate profiles of competing products (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010) and, by extension, to green certification and labelling (Rajagopalan *et al.*, 2011). Although such lifecycle-based performance measurements may provide a useful way of making sound environmental decisions regarding a product supply chain, there is no current standardised approach to benchmark product categories. In addition, lifecycle assessment (LCA) based approaches used for benchmarking have generally adopted process-based methodologies (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010 and Ibáñez-Forés *et al.*, 2013). Traditional or process-based LCA approaches inherently suffer from system boundary truncation and as such are not able to deal with the complexity of supply chains (Acquaye *et al.*, 2011; Majeau-Bettez and *et al.*, 2011). In designing and developing the benchmarking framework based on the product supply chain carbon map, the Environmental Input-Output approach (Wiedmann, 2009 and Acquaye and Duffy, 2010), developed in this paper as a 2-region (UK and Rest of the World) Input-Output Framework is adopted (Refer to Section 3). This provides an extended system boundary for the benchmarking framework and helps address the complexity of product supply chains in terms of the globalized nature of the interconnected product, process and service inputs involved in product supply chains at every tier (Finnveden *et al.*, 2009 and Rodrigues *et al.*, 2010).

As Shaw *et al.* (2010) pointed out, many firms are not in a position to conduct benchmarking activities due to the lack of approaches that would enable them to measure their environmental performance and compare it to industry standards or competitors. This paper hopes to add to the knowledge base by presenting a systematic approach to benchmark the performance of product supply chains through the use of maps developed based on a system wide view of the whole supply chain. This also provides firms the opportunity to undertake cross-sectoral benchmarking (McNamee, 2001) by comparing the performance of their supply chains against other similarly structured firms when measured against industry-level standards. In addition, opportunities for continuous environmental improvement of product supply chains can be identified and pursued.

2.2 Supply Chain Mapping

A map can be defined as a spatial representation of an environment (Muehrcke and Muehrcke, 1992). A supply chain map can therefore be described as a graphical representation of the spatial and functional relationships between the various actors in the organisation's supply chain network. A supply chain map must combine two characteristics: the immediacy of the information to be shared and the capability of exceeding individual understanding and vision (Gardner and Cooper, 2003). The appearance of maps can vary significantly from application to application and across disciplines. An example is provided by geographic information systems (GISs) that provide maps tied to databases capable of displaying several outputs depending on selected variables, such as population density, income, soil type. Applying these concepts to a supply chain context can therefore result in a clear understanding of the exact flow of materials and impacts along the supply chain and hence form the basis for managing and benchmarking the environmental performance of the supply chain.

Several reasons have been cited as motivation for starting a supply chain mapping process (Gardner and Cooper, 2003). However, these benefits have not previously been extended to form the basis for benchmarking the environmental performance measurement of the supply chain.

According to the current state of the art, several methodologies are available for mapping purposes (for a complete review see, Min and Zhou, (2002) :

- GIS-based methods, that allow for a geographical representation of the supply chain;
- Network-based methods, allowing for representing flows across the supply chain thanks to a node-edge perspective. This is mainly utilised in the operational research literature for setting and solving supply chain optimisation problems;
- Value Stream methods, that allow for identifying value creation hot-spots within the supply chain, usually used in reducing waste and idle times.

The current literature does not provide any approach for mapping a supply chain from a low-carbon perspective. Mason *et al.* (2008) develop a new mapping technique based on lean thinking paradigm and value stream mapping, attempting to adapt this to the requirements of industrial ecology. It draws on systems theory to assert that lean thinking is holistic in nature and illustrates that supply chain waste reduction can find wider application in an environmental context. Farris (2010) also used geo-visualization techniques to create strategic supply chain maps using real economic industry exchange data.

In addition to the academic literature, several practitioner-oriented mapping tools have been developed. For instance, PUMA (2011) highlighted how supply chain maps can be used to inform an Environmental Profit and Loss Account by placing a monetary value on the environmental impacts along the entire supply chain. Furthermore, TRUTHSTUDIO (2013) provides visualisation techniques of supply chains in order to support decision making. These examples demonstrate the potential importance of supply chain mapping. Despite the operational benefits and support that these practitioner tools can provide, there seems to be a lack of theoretical foundation, particularly in using approaches in supply chain mapping for benchmarking purposes.

According to Gardner and Cooper (2003) supply chain maps can differ on the basis of their perspective. In this paper, we adopt industry-level supply chain maps in such a way to set a benchmark against which the performance of product-level supply chains can be measured. Figure 1 provides the framework for the benchmarking process.

<Insert Figure 1>

Indeed, the potential of using supply chain maps for benchmarking can be developed for a whole industrial sector (a top-down approach). This can highlight opportunities for companies to measure their own product-level performance (in terms of relative resource requirements and carbon emissions for instance) against industrial benchmarks.

3 Methodologies

In this study, Input-Output (IO) methodology applied within a multi-regional (UK and Rest-of-the-World) framework is adopted to develop the supply chain maps and consequently benchmarking the environmental sustainability (in terms of resource requirements and carbon emissions) of product supply chains against industry-level standards. This methodology is based on the principles of lifecycle assessment (LCA). The usefulness of LCA lies in its application, the nature of the presentation of the results and the relevance and implications of the study. In this paper, the multi-regional input-output LCA methodology is chosen because the benchmarking approach taken is top-down or an industry-level one. Other LCA methodologies such as process LCA analysis and hybrid LCA (Bilec *et al.*, 2006 and Acquaye *et al.*, 2011) that make use of product specific data (a bottom-up approach) would not be wholly suitable. The top-down approach also offers the advantage of overcoming the complexity of supply chains by ensuring the complete visibility of the whole network. Indeed, environmentally-extended multi-regional input-output analysis has emerged as the favoured method for quantifying emission embodiments (Wiedmann *et al.*, 2007; Wiedmann, 2009; Acquaye *et al.*, 2011; Kanemoto *et al.*, 2011; Skelton *et al.*, 2011 and Barrett and Scott, 2012). The limitations of this methodology are discussed in Section 5.3. In this study, the industrial supply chain that produces 1 tonne of steel in the UK is used to illustrate these developments. The advancements in MRIO analysis follow on from the basic developments of IO analysis, see *inter alia:* Peters and Hertwich (2009) and Wiedmann *et al.*, (2010).

3.1 General Input-Output Model

The basic input-output (IO) model which is well documented is used as the underlying methodology in this paper (ten Raa, 2007; Ferng, 2009; Miller and Blair, 2009 and Minx *et al.*, 2009). The methodology is very useful in ensuring the whole visibility of the supply chain (Acquaye and Duffy, 2010; Mattila *et al.*, 2010 and Wiedmann *et al.*, 2011). As a result, a whole lifecycle perspective, which is a key principle of green supply chain management, is adopted (Carter and Easton, 2011; Genovese *et al.*, 2013b).

3.2 Multi-Regional Input-Output (MRIO) Model

The UK MRIO model used to develop the supply chain maps is constructed as a 2-region model (UK and Rest-of-the World, the latter indicated as ROW in the following) framework. The main data sources used are the 2-region Multi Regional Input-Output (MRIO) data expanded upon by Wiedmann *et al.* (2010) to include MRIO tables split between the UK and ROW.

Following on from the basic IO methodology in which the technical coefficient matrix, Leontief inverse matrix and final demand matrix are clearly defined (Miller and Blair, 2009), the expansions reported in the following can be made.

The technical coefficient matrix can be reformulated as:

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_{UK} & \boldsymbol{A}_{exp} \\ \boldsymbol{A}_{imp} & \boldsymbol{A}_{ROW} \end{bmatrix}$$

In this case, $\boldsymbol{A}$ becomes the 2-region MRIO model technical coefficient matrix. This includes the respective technical coefficient matrices for UK domestic $\boldsymbol{A}_{UK}$, UK imports from ROW $(\boldsymbol{A}_{imp})$, UK exports to ROW $(\boldsymbol{A}_{exp})$ and ROW domestic $(\boldsymbol{A}_{ROW})$. $\boldsymbol{A}_{UK}$, $\boldsymbol{A}_{imp}$, $\boldsymbol{A}_{exp}$ and $\boldsymbol{A}_{ROW}$ are all of dimensions $178\ x\ 178$; hence, $\boldsymbol{A}$ and $\boldsymbol{I}$ (the Identity Matrix) are therefore of dimensions $356\ x\ 356$. Full details of sectoral classifications are available in Appendix 1.

The Technical Coefficient Matrix for UK imports $\boldsymbol{A}_{imp}$ is therefore defined as:

$$\boldsymbol{A}_{imp} = \left[\frac{q_{ij}^{(ROW,UK)}}{x_j} \right]$$

Where: $q_{ij}^{(ROW,UK)}$ represents elements of imports input-output table indicating the input of product (i) from ROW into the industry (j) of the UK while x_j represents the total output of UK industry, (j).

Given that the demand for steel can result from domestic (or UK) production or from imported (ROW) production, the final demand matrix can be presented such that:

$$\boldsymbol{y} = \begin{bmatrix} \underline{y}_{(UK,UK)} & \underline{y}_{(UK,ROW)} \\ \underline{y}_{(ROW,UK)} & \underline{y}_{(ROW,ROW)} \end{bmatrix}$$

Where: $\underline{y}_{(UK,UK)}$ and $\underline{y}_{(ROW,ROW)}$ represents the domestic (UK) demand for UK products and ROW demand for ROW products respectively. Likewise, $\underline{y}_{(UK,ROW)}$ and $\underline{y}_{(ROW,UK)}$ represents ROW demand for UK products and UK demand for ROW products respectively. Indeed, by interconnecting the domestic and ROW input-output tables into a 2-region MRIO table, the model can overcome the complexity of product supply chains as a result of the globalized nature of the interconnected product, process and service inputs at every tier in the supply chain. In this study, we assume UK demand for products produced in the UK and from the rest of the world. Hence, $\underline{y}_{(UK,ROW)}$ and $\underline{y}_{(ROW,ROW)}$ are set to zero. Therefore, the final demand matrix (now of dimension $356\ x\ 1$) becomes a column matrix:

$$\underline{y} = \begin{bmatrix} \underline{y}_{(UK,UK)} \\ \underline{y}_{(ROW,UK)} \end{bmatrix}$$

Hence the total (direct and indirect) requirements needed by an industry to produce a given final demand using the MRIO model become:

$$\underline{x} = \left(\begin{bmatrix} \boldsymbol{I} & 0 \\ 0 & \boldsymbol{I} \end{bmatrix} - \begin{bmatrix} \boldsymbol{A}_{UK} & \boldsymbol{A}_{exp} \\ \boldsymbol{A}_{imp} & \boldsymbol{A}_{ROW} \end{bmatrix} \right)^{-1} \cdot \begin{bmatrix} \underline{y}_{(UK,UK)} \\ \underline{y}_{(ROW,UK)} \end{bmatrix}$$

This MRIO model forms the basis for the development of the industry-level supply chain map used to benchmark the performance of product supply chains in terms of relative resource requirements. To extend the assessment to cover carbon emissions, the MRIO model is combined with an industry-level environmental model.

3.3 Environmentally Extended MRIO Model

Input-Output analysis can be extended to an Environmental Input-Output (EIO) lifecycle assessment (LCA) to generate results which can be used in the general assessment of supply chain emissions and to benchmark product supply chains in terms of carbon emissions.

Given that $\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y}$ defines the total direct and indirect requirements needed to produce an output x for a given final demand, y; the EIO LCA can therefore be defined in a generalised form as:

$$\underline{E} = \boldsymbol{E}_{io} \cdot \underline{x} = \boldsymbol{E}_{io} \cdot (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y}$$

Where $\boldsymbol{E}_{io}$ is the direct emissions intensity (kg CO_2-eq/£) of the IO industries and $\boldsymbol{E}_{io} \cdot (\boldsymbol{I} - \boldsymbol{A})^{-1}$ the total (direct and indirect) emissions intensities (kg CO_2-eq/£).

By extension, the matrix $\boldsymbol{E}_{io}$ expressed in terms of the MRIO structure becomes:

$$\boldsymbol{E}_{io} = \begin{bmatrix} \boldsymbol{E}_{UK} & 0 \\ 0 & \boldsymbol{E}_{ROW} \end{bmatrix}.$$

Hence, the environmental-extended MRIO lifecycle assessment takes the following form, where the matrix $(\underline{E})$ describes the total emissions:

$$\underline{E} = \begin{bmatrix} \boldsymbol{E}_{UK} & 0 \\ 0 & \boldsymbol{E}_{ROW} \end{bmatrix} \cdot (\begin{bmatrix} \boldsymbol{I} & 0 \\ 0 & \boldsymbol{I} \end{bmatrix} - \begin{bmatrix} \boldsymbol{A}_{UK} & \boldsymbol{A}_{exp} \\ \boldsymbol{A}_{imp} & \boldsymbol{A}_{ROW} \end{bmatrix})^{-1} \cdot \begin{bmatrix} \underline{y}_{(UK,UK)} \\ \underline{y}_{(ROW,UK)} \end{bmatrix}$$

This environmentally extended MRIO model forms the basis for the development of the industry-level supply chain map used to benchmark the performance of product supply chains in terms of carbon emissions.

4 Development of Supply Chain Maps

As mentioned above, the development of supply chain maps may be beneficial as it can provide multiple sources of information for benchmarking and performance measurement purposes. Indeed, supply chain maps can show the relative contribution of resources requirements from supply chain sectors and tiers needed to produce the final product (in this instance, 1 tonne of steel). Secondly, the supply chain maps can report the relative emissions impact of each resource demanded by the product supply chain at each supply chain tier. The following sub-sections will illustrate how the industry-level supply chain maps were developed based on the MRIO methodology presented in Section 3 and used to benchmark the performance of product-level supply chains.

4.1 Resource Requirements from Supply Chains Sectors and Tiers

In a generalised form, the final demand matrix and the Leontief Inverse matrix can be expressed as: $\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y}$.

As such, at a whole supply chain level, considering the total sectoral demands for product *k*, the associated inputs from all product sectors are calculated as:

$$\underline{x} = (\boldsymbol{A}^0 + \boldsymbol{A}^1 + \boldsymbol{A}^2 + \boldsymbol{A}^3 + \boldsymbol{A}^4 + \cdots) \cdot \underline{y_k} = [x_{i,k}] \; with \; k \in J$$

Where:

$\underline{y_k}$ represents the final demand matrix for product k. Given that the study assumes UK demand, $\underline{y_k} = \begin{bmatrix} \underline{y}_{(UK,UK)} \\ \underline{y}_{(ROW,UK)} \end{bmatrix}$. In the same way, considering the same product *k*, for each tier (n) in its supply chain the associated inputs from product sectors are calculated as:

$$\underline{x}^{tier\ (n)} = \boldsymbol{A}^n \cdot \underline{y_k} = [x_{i,k}^{tier\ (n)}] \; with \; k \in J$$

Therefore, relative resource requirements in the supply chain of the product *k* from product sectors *i* at each tier (n) can be computed as:

$$\delta_{i,k}^{tier\ (n)} = \frac{x_{i,k}^{tier\ (n)}}{\sum_i x_{i,k}}$$

The supply chain maps will report the values $\delta_{i,k}^{tier\ (n)}$ for the selected product *k*, at each tier (n) requiring resource inputs from each product sector *i* in the economy, taking into account both UK and ROW inputs. In this paper, supply chain *tiers* are defined as the different levels of inter-industry resource demand, and consequently carbon emissions, across the economy which contribute to resources usage, and hence carbon emissions, within the reference industry supply chain being benchmarked.

4.2 Emissions Impacts from Supply Chains Sectors and Tiers

The technical coefficient matrix in the MRIO format is written as: $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_{UK} & \boldsymbol{A}_{exp} \\ \boldsymbol{A}_{imp} & \boldsymbol{A}_{ROW} \end{bmatrix}$. Given that the study assumes UK production but with supply chain resource input (demand) from both the UK and the ROW; the technical coefficient matrix is re-written as: $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_{UK} & \boldsymbol{0} \\ \boldsymbol{A}_{imp} & \boldsymbol{0} \end{bmatrix}$.

The MRIO EIO lifecycle assessment equation becomes:

$$\underline{E} = \begin{bmatrix} \boldsymbol{E}_{UK} & 0 \\ 0 & \boldsymbol{E}_{ROW} \end{bmatrix} \cdot \left(\begin{bmatrix} \boldsymbol{I} & 0 \\ 0 & \boldsymbol{I} \end{bmatrix} - \begin{bmatrix} \boldsymbol{A}_{UK} & 0 \\ \boldsymbol{A}_{imp} & 0 \end{bmatrix} \right)^{-1} \cdot \underline{y_k}$$

At a whole supply chain level, considering the production of a product *k*, the associated impacts as a result of resource inputs from each product sector in the economy (both UK and ROW) can be formulated as:

$$\underline{E} = \begin{bmatrix} \boldsymbol{E}_{UK} & 0 \\ 0 & \boldsymbol{E}_{ROW} \end{bmatrix} \cdot (\boldsymbol{A}^0 + \boldsymbol{A}^1 + \boldsymbol{A}^2 + \boldsymbol{A}^3 + \boldsymbol{A}^4 + \cdots) \cdot \underline{y_k} = [e_{i,k}] \; with \; k \in J$$

Therefore, considering a product *k*, for each tier (n) in its supply chain, the associated impacts (E_n) are calculated as:

$$\underline{E_n} = \begin{bmatrix} \boldsymbol{E}_{UK} & 0 \\ 0 & \boldsymbol{E}_{ROW} \end{bmatrix} \cdot \boldsymbol{A}^n \cdot \underline{y_k} = [e_{i,k}^{tier\,(n)}] \; with \; k \in J$$

Thus, relative emissions impacts in the supply chain of the product *k* as a result of using resources from products sectors at each tier (n) can be computed as:

$$\varepsilon_{i,k}^{tier\,(n)} = \frac{e_{i,k}^{tier\,(n)}}{\sum_i e_{i,k}}$$

The supply chain maps will report the values $\varepsilon_{i,k}^{tier\,(n)}$ for the selected product *k*, at each tier (n) as a result of using resource inputs from both UK and ROW in its supply chain.

4.3 Supply Chain Maps Structure

By using the previously introduced $\varepsilon_{i,k}^{tier\,(n)}$ and $\delta_{i,k}^{tier\,(n)}$ indicators, supply chain maps capable of showing the relative contribution of resource requirements used in each tier of supply chain to produce the final product and the relative emissions impacts can be represented and reported. To this aim, appropriate thresholds should be defined in order to classify sectors according to their inputs and their emissions.

As outlined in Tables 1 and 2, a sector *i* will be represented in the supply chain map at tier (n) if its relative input $\delta_{i,k}^{tier\,(n)}$ is greater than the threshold for the given tier or if its relative emission intensity $\varepsilon_{i,k}^{tier\,(n)}$ is greater than 1%.

<Insert Table 1>

<Insert Table 2>

Figure 2 shows the principles adopted in developing the supply chain map. Each sector is represented by a node (a circle) within the network diagram; the colour of the circle will be representative of the emission intensity level; each tier is represented by a dashed box including one or more nodes. Inputs from each sector are represented by arrows, weighted by the strength of relative resource demand.

For each sector, at each tier level, the following information is reported:

- The relative resource requirement for sector i at tier (n) $\delta_{i,k}^{tier\,(n)}$;
- The relative emissions intensity for sector i at tier (n) $\delta_{i,k}^{tier\,(n)}$.

<Insert Figure 2>

Weights of the arrows and colours of the nodes will be representative of the different intensities of both resource demands and emissions. Tables 3, 4 and 5 report the adopted thresholds and symbols, also allowing for reporting both domestic and import inputs. Thresholds are flexible and can be adapted based on the specific application.

<Insert Table 3>

<Insert Table 4>

<Insert Table 5>

5 Results and Discussions

5.1 Supply chain map as a benchmark for industry-level environmental performance measurement

Figure 3 illustrates the complete supply chain maps representing the average UK production of 1 tonne of steel obtained through the procedure highlighted in Section 4. Details of the Input-Output classification and links to specific sectors are presented in Appendix 1.

The supply chain maps presented here re-affirm the fact that inputs having significant emissions impacts within a product supply chain are not limited to direct inputs or domestic supplies but may also include upstream and imported supply chain inputs. As such, any approach used to develop performance benchmarks must be able to capture such inputs that may have significant impacts on the product supply chain. For instance, it can be observed from Figure 3 that Tier 1 supply chain inputs such as Sector 112 (Recycling of Metal Waste and Scrap - domestic), according to the thresholds set in Section 4.3, can be described as a high carbon emissions hot-spot within the average UK steel supply chain. As such, this represents an opportunity for the focal firm to work closely with its domestic or UK supplier of scrap metal to improve their environmental performance. Additionally, Sector 80 (Basic Metal – both domestic and import), Sector 111: Recycling (import), Sector 114: Electricity Production from Gas (domestic), Sector

115: Electricity Production from Coal (domestic) can all be described as Moderate Tier 1 emissions hot-spots within the supply chain.

The supply chain map presented as a benchmark for environmental performance measurement demonstrates its usefulness as a graphical representation of the functional relationships between actors (in this instance, sectors at the industry-level) within the supply chain, showing the relative resource requirements of high resource inputs and high carbon emission paths within the product supply chain.

The benchmarking framework has been developed using national-level data for the steel industry; hence it forms the basis for setting an industry-level benchmark against which firms can measure the performance of their product supply chains. This can be both in terms of relative resource requirements from supply chain sector inputs and carbon emissions contributions.

<Insert Figure 3>

Results summarised in the map can be further analysed. The demand for resource inputs into a supply chain can be classed as intermediate demand and final demand. Intermediate demand (represented here as Tier 1, Tier 2, Tier 3, etc) describes the resources used by other sectors that are then used in producing other product and services that ultimately are used in directly producing the final demanded product (represented here as Tier 0).

Figure 4 shows a different perspective on the supply chain map. By employing the same representation methodology and the same threshold values, it was developed by aggregating the relative resource requirement and supply chain impacts of the 178 disaggregated sectors representing the wider economy into one of eighteen broader sectors namely: Agriculture, Forestry, Fishing, Mining, Food, Textiles, Wood & Paper, Fuels, Chemicals, Minerals, Metals, Equipment, Utilities, Construction, Trade, Transport & Communication, Business Services and

Personal Services. These market segments are referenced respectively as A-R on the supply chain maps in Figure 4. Refer to Appendix 2 for details. This supply chain map helps to identify, in a more intuitive way, market segments which should be prioritized in terms of de-carbonization and resource efficiency efforts.

<Insert Figure 4>

Figure 5 also shows the breakdown in the relative split between Domestic and Imports for all the intermediate resource demand associated with the steel producing sector in the UK. Most of the supply chain input requirements (approximately 76%) are sourced from the UK. However, as typical of contemporary complex and global supply chains, it can be observed that for the UK steel sector, an average of 23% of these resource inputs are imported. This percentage represents a benchmark for the sector average against which firms can measure themselves. It therefore enables an individual firm to compare its performance with other similarly structured firms. This is a cross-sectoral measure which enables comparisons with strategic peers (McNamee *et al.*, 2001). Furthermore, it also gives an indication of the measurement of supply chain risk in terms of reliance on imported supply chain inputs.

<Insert Figure 5>

As already shown in Figure 4, the whole economy (both domestic and import) represented by the input-output classification from which a supply chain derives its resources can be represented by 18 different broad market segments. Figure 6 further illustrates the average sectoral emissions in kg CO_2-eq for 1 tonne UK production of steel. From the analysis, the carbon emissions benchmark for the steel sector in the UK against which the environmental sustainability performance of a steel product supply chain can be measured against was estimated to be 1158.22 kg CO_2-eq per tonne. The supply chain contribution is made up of 91.2% of carbon emissions impacts from the domestic supply chain and 8.8% of carbon emissions impacts from the imported supply chain. As can be observed from Figure 6, the significant sector contributions are Metals Sector (domestic): 861.1 kg CO_2-eq or 74.3%; Utilities Sector (domestic): 101.6 kg CO_2-eq or 8.8%; Metals Sector (import): 50.2 kg CO_2-eq or 4.34%; Mining Sector (domestic): 31.0 kg CO_2-eq or 2.7%; Transport and Communications Sector (domestic):25.0 kg CO_2-eq 2.2%.

<Insert Figure 6>

A detailed breakdown of the top 10 emitting sectors in kg CO_2-eq for the average production of 1 tonne of steel in the UK is presented in the bar chart in Figure 7. The biggest carbon emitters are the direct domestic resources used in the steel manufacturing process.

<Insert Figure 7>

In addition to the supply chain carbon map, analyses of the derived results can assist the focal firm to gain further insight into benchmarking the environmental performance of its product supply chain against industry standards in order to identify opportunities to improve environmental sustainability performance.

5.2 Supply Chain Managerial Implications

In the benchmarking process, the focal firm responsible for the production of the final product (in this instance steel) takes responsibility as the supply chain leader. Using primary data from its own production process and supply chain, relative resource inputs and carbon emissions at each tier within the supply chain can be identified and matched to the supply chain map developed for the industry-level using the input-output classifications presented in Appendix 1.

In this paper, the steel supply chain presented represents a hierarchical supply chain relationship between the focal firm and its suppliers. As such, the main managerial/administrative and operational implications and challenges are the responsibility of the focal firm. The focal firm must encourage and promote a two-way data and knowledge exchange across the supply chain (regarding, for instance, production supplies, carbon emissions impacts, resource usage) in order to avoid an asymmetric information state. Supplier engagement must also be led by the focal firm because it is essential that activities of suppliers identified as carbon emissions hotspots in upstream tiers, such as Tier 1: 112- 'Recycling of Metal Waste and Scrap' in this example, must be addressed to reduce the overall impacts. Such supply chain collaborations and partnerships can help turn strategic intent into an organisational reality (Wagner *et al.*, 2002).

The task of overseeing the implementation and analysis of such a framework should fall within the remit of the sustainability leadership of the company. In fact, such sustainability measures integrated within organisations should be backed by a business case in order that they do not conflict with the primary goals of managers, who are urged to obtain immediate or short-term performance improvement (Burritt *et al.*, 2011). According to Quinn and Dalton (2009) such measures should be championed by the 'Director of Sustainability' or 'Sustainability Manager'; however for other organisations, the necessary structure can involve the set-up of teams which would enable the full integration of such sustainability practices.

The development of the supply chain maps as a benchmark can also serve as evidence for a base-case environmental scenario analysis, example carbon emission. By implementing low carbon intervention measures at identified hot-spots, different interventions scenarios can be tested to establish which is likely to have the biggest impact and/or represents the best value in terms of future economic and environmental sustainability and competitiveness. This is particularly relevant as economic sustainability remains a key driver for greening activities, with firms perceiving the need to establish robust business cases regarding the payback of interventions to ensure costs as well as emissions are reduced. Such scenario analysis will provide visible evidence and also allow for intervention measures to be prioritised and designed with the information provided by the benchmark presented in the supply chain map. This visible process of strategic emission reduction will allows firms to promote their green credentials to their supply chain partners and customers in an increasingly environmentally conscious climate where green-wash no longer satisfies (Lyon and Maxwell, 2011).

5.3 Supply Chain Challenges and Methodological Assumptions

The environmental performance benchmark presented poses practical supply chain management challenges. In addition, its application must be communicated within the scope of the assumptions inherent in the methodology used in the developments. Access to product supply chain data is a major practical challenge in measuring the environmental performance of a product supply chain against the industry-level benchmark that has been presented. Focal firms must be able to collect supply chain data for their own processes as well as that of their supply chain partners. Data gathering and sharing therefore becomes a pivotal activity. This is because primary supply chain data of the product whose environmental performance is to be measured must be matched to the supply chain maps using the input-output classifications. Although this can be a challenging and time consuming exercise, by selling the fact that benefit from knowledge generation and opportunities for environmental performance improvements are tied to economic gains, the performance measurement exercise can act as a driver for supply chain partners to collaborate more effectively.

Input-output analysis, the methodology underlying the developments (as presented in Section 3) by its nature suffers from inherent limitations (Hendrickson *et al.*, 1998 and Acquaye and Duffy 2010). For instance, it assumes homogeneity which proposes that each sector produces a uniform output using identical inputs and processes. However, this is not the case since each sector may be a representation of many different products or services, and even for the same product, different technologies may be used in its production. In the example presented for the steel supply chain map, steel is a typical product of Input-Output Sector 80 but this may also represent other products. To address this assumption, disaggregation techniques can be applied whereby a particular sector of interest can be disaggregated into two separate sectors; a unique sector for the product of interest and another sector for all other products belonging to that sector. This ensures a distinctive sector is allocated for the product supply chain even at the industry-level. Typical examples of this disaggregation analysis have been undertaken in the literature (see for instance, Wiedmann *et al*., (2011) and Li *et al*., (2012)).

The proportionality assumption in IO analysis requires that in any production process all inputs are used in strictly fixed proportions; as such there is a linear correlation between production inputs and outputs and consequently in environmental impacts (Baral and Bakshi, 2010). The proportionality assumption is accepted in the use of input-output frameworks (Baral and Bakshi, 2010) mainly because of the lack of data (Tukker and Dietzenbacher, 2013). Hendrickson *et al*. (1998) also note that the linear proportionality assumption could be sufficiently accurate even if the underlying effects are nonlinear. This is because in some cases, the best available estimate still might be a linear extrapolation.

As such, the industry-level benchmarking undertaken using the IO framework should be communicated as representing the first instance for firms to manage environmental performance of their product supply chain and identify opportunities for continuous improvements. The supply chain framework shown and used to undertake the benchmarking should therefore be considered in context with respect to the practical challenges in its implementation. For instance, in other cases, the use of market-based mechanisms such as emissions certificates or the deliberate re-utilization of resources may also result in reduced emissions. As such, an accurate reflection of the actual level of environmental performance of an organisation's supply chain may not be revealed.

6 Conclusions

The paper presents a systematic benchmarking approach which utilizes the multi-regional input-output lifecycle assessment method as a basis for developing supply chain maps for industrial-level carbon emissions performance measurement. The steel industry supply chain is used to demonstrate the application. The benchmarking approach can enable entire supply chain impacts and resource use for all tiers of the supply chain, including domestic and import flows to be evaluated. In addition, it can provide the basis for individual firms to compare their environmental performance against other similarly structured firms through cross-sectoral benchmarking.

It has been well-established that supply chain performance measurement and benchmarking provides opportunities for businesses to identify ways to improve the sustainability (economic, social and environmental) of their supply chains. However, approaches to measure the performance of these systems are difficult for a number of reasons. These includes: the lack of insight in achieving a fully integrated supply chain (Gunasekaran *et al.*, 2001); complexities of the supply chains (Beamon, 1999); non-standardized data, geographical differences, lack of agreed upon metrics and benchmarking approaches (Hervani *et al.*, 2005). This paper has contributed to the knowledge base of this research area by presenting a systematic approach of setting an industry-level benchmark for product supply chain environmental performance measurement by addressing some of these challenges. A general framework for the process is presented in Figure 1. The methodological framework is underpinned by the use of multi-regional input-output (MRIO) analysis to develop product supply chain maps. This ensures that both direct and indirect carbon emissions impacts are systematically assessed. This is in line with the suggestion by Lee (2011) who emphasised that although companies are increasingly adopting a life cycle perspective of their carbon impacts in their products and services, manufacturers should identify and consider the indirect carbon emissions if they wish to manage carbon footprint and performance in operations. The steel sector was used to demonstrate the approach, which can be extended to other product supply chains. In addition, carbon emissions were chosen as the main environmental sustainability indicator because it is the most commonly cited environmental impact.

The approach also satisfies the key characteristics in the development of effective performance management systems. These key characteristics are: inclusiveness (measurement of all pertinent aspects), universality (allow for comparison under various operating conditions), measurability (data required are measurable) and consistency (measures consistent with organization goals). The use of the MRIO framework ensures that there is complete visibility of the supply chain hence all domestic and imported resource inputs into the supply chain are captured; hence, this satisfies the inclusiveness characteristic. The compilation of input-output tables is now a routine practice governed by UN standards; hence the analysis undertaken in this study can be replicated for other product supply chains and in other countries and regions under different scenarios, which satisfies the universality characteristic. In addition, the quantitative approach used in the development of the supply chain maps is underpinned by a systematic method used to set an industry-level benchmark for the environmental sustainability of product supply chains, hence, satisfying the consistency characteristic. It also uses and generates measurable supply chain data, hence, satisfying the measurability characteristic.

The industry-level benchmark for product supply chain performance measurement can provide the first step firms to manage environmental performance and identify opportunities for continuous improvements. The focal firm must take on the responsibility of leading data gathering from supply chain partners, information and knowledge sharing in order to facilitate the benchmarking process using primary data collected from its own production process and supply chain. The results would therefore also enable companies to undertake industrial cross-sectoral benchmarking based on comparisons with results generated bottom-up from company-specific supply chain primary data. Data sharing and closer supply chain collaboration are therefore crucial to making this a success by improving the sustainability of product supply chains and promoting knowledge generation and dissemination. This can enhance the design of supply chain networks and implementation of measures in operations to reduce carbon emissions. The calculations and results represent industry-level benchmarks generated from country specific input-output secondary data.

Further research will be aimed at extending the analysis framework to other product supply chains in different sectors and to other environmental indicators, while testing the practical application of the developed maps as benchmarking tools in practice.

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Appendix 1: Detailed breakdown of Input-Output sector classifications

No.	Input-Output Classification	No.	Input-Output Classification	No.	Input-Output Classification
1	Conventional Growing of cereals; vegetables; fruits and other crops	61	Inorganic basic chemicals	121	Collection; purification and distribution of water
2	Organic Growing of cereals; vegetables; fruits and other crops	62	Organic basic chemicals	122	Construction (other than commercial and domestic buildings)
3	Growing of horticulture specialities and nursery products	63	Fertilisers and nitrogen compounds	123	Construction of commercial buildings
4	Conventional Farming of livestock (except poultry)	64	Plastics and synthetic rubber in primary forms (non-PVC)	124	Construction of domestic buildings
5	Organic Farming of livestock (except poultry)	65	PVC plastics in primary forms	125	Sale; maintenance and repair of motor vehicles; and motor cycles; retail sale of automotive fuel
6	Conventional Farming of poultry	66	Pesticides and other agro-chemical products	126	Retail sale of automotive fuel
7	Organic Farming of poultry	67	Paints; varnishes and similar coatings; printing ink and mastics	127	Wholesale trade and commission trade; except of motor vehicles and motor cycles
8	Forestry; logging and related service activities (conventional)	68	Pharmaceuticals; medicinal chemicals and botanical products	128	Retail trade; except of motor vehicles and motor cycles
9	Forestry and logging and related service activities ('sustainable' / FSC)	69	Soap and detergents; cleaning and polishing preparations; perfumes and toilet preparations	129	Repair of personal and household goods
10	Fishing	70	Other chemical products	130	Hotels and accommodation
11	Fish farming (non-organic)	71	Man-made fibres	131	Restaurants; cafes; bars etc.
12	Fish farming (organic/sustainable)	72	Rubber products	132	Passenger transport by railways
13	Mining of coal and lignite; extraction of peat	73	Plastic plates; sheets; tubes and profiles	133	Freight transport by inter-urban railways
14	Extraction of crude petroleum and natural gas and Service activities incidental to oil and gas extraction; excluding surveying	74	Plastic packing goods	134	Buses and coaches
15	Mining of uranium and thorium ores	75	Glass and glass products	135	Tubes and Trams
16	Mining of iron ores	76	Ceramic goods	136	Taxis operation
17	Mining of non-ferrous metal ores; except uranium and thorium ores	77	Bricks; tiles and other structural clay products for construction	137	Freight transport by road
18	Mining and quarrying of stone; gravel; clays; salt; etc.	78	Cement; lime and plaster	138	Transport via pipeline
19	Conventional meat and meat products (excl. poultry)	79	Articles of concrete; plaster and cement; cutting; shaping and finishing of stone; manufacture of other non-metallic products	139	Passenger sea and coastal water transport + Passenger inland water transport
20	Organic meat and meat products (excl. poultry)	80	Basic iron and steel and of ferro-alloys; manufacture of tubes and other first processing of iron and steel	140	Freight sea and coastal water transport + Other inland water transport
21	Conventional poultry meat and poultry meat products	81	Copper; Lead; Zinc; Tin and other basic precious and non-ferrous metals (not Aluminium)	141	Passenger air transport
22	Organic poultry meat and poultry meat products	82	Aluminium	142	Freight and other air transport
23	Fish and fish products	83	Casting of metals	143	Supporting and auxiliary transport activities: travel agencies; cargo handling; storage;
24	Conventional Fruit and vegetables	84	Structural metal products	144	Postal and courier services
25	Organic Fruit and vegetables	85	Tanks; reservoirs and containers of metal; manufacture of central heating radiators and boilers; manufacture of steam generators	145	Telecommunications
26	Vegetable and animal oils and fats	86	Forging; pressing; stamping and roll forming of metal; powder metallurgy; treatment and coating of metals	146	Banking and financial intermediation; except insurance and pension funding
27	Dairy products (conventional)	87	Cutlery; tools and general hardware	147	Insurance and pension funding; except compulsory social security
28	Organic dairy products	88	Other fabricated metal products	148	Auxiliary financial services

29	Grain mill products; starches and starch products	89	Machinery for the production and use of mechanical power; except aircraft; vehicle and cycle engines	149	Real estate activities with own property; letting of own property; except dwellings
30	Prepared animal feeds	90	Other general purpose machinery	150	Letting of dwellings; including imputed rent
31	Bread; rusks and biscuits; manufacture of pastry goods and cakes (conventional)	91	Agricultural and forestry machinery	151	Real estate agencies or activities on a fee or contract basis
32	Organic bread; rusks and biscuits; manufacture of pastry goods and cakes	92	Machine tools	152	Renting of cars and other transport equipment
33	Sugar	93	Other special purpose machinery	153	Renting of machinery and equipment; excl. office machinery and computers
34	Cocoa; chocolate and sugar confectionery	94	Weapons and ammunition	154	Renting of office machinery and equipment including computers
35	Other food products	95	Domestic appliances (e.g. white goods)	155	Renting of personal and household goods
36	Alcoholic beverages	96	Computers and other office machinery and equipment	156	Computer services and related activities
37	Production of mineral waters and soft drinks	97	Electric motors; generators and transformers; manufacture of electricity distribution and control apparatus	157	Research and development
38	Tobacco products	98	Insulated wire and cable	158	Legal activities
39	Preparation and spinning of textile fibres	99	Electrical equipment not elsewhere classified	159	Accounting; book-keeping and auditing activities; tax consultancy
40	Textile weaving	100	Electronic valves and tubes and other electronic components	160	Business and management consultancy activities; management activities; market research and public opinion polling
41	Finishing of textiles	101	Television and radio transmitters and line for telephony and line telegraphy	161	Technical consultancy; technical testing and analysis; architectural and engineering related activities
42	Made-up textile articles; except apparel	102	Television and radio receivers; sound or video recording or reproducing apparatus and associated goods	162	Advertising
43	Carpets and rugs	103	Medical; precision and optical instruments; watches and clocks	163	Other business services
44	Other textiles	104	Motor vehicles; trailers and semi-trailers	164	Public administration (not defence); compulsory social security
45	Knitted and crocheted fabrics and articles	105	Building and repairing of ships and boats	165	Public administration – defence
46	Wearing apparel; dressing and dying of fur	106	Railway transport equipment; motorcycles; bicycles and transport equipment n.e.c.	166	Primary; secondary and other education
47	Tanning and dressing of leather; manufacture of luggage; handbags; saddlery and harness	107	Aircraft and spacecraft	167	Higher-level education
48	Footwear	108	Furniture	168	Human health and veterinary activities
49	Wood and wood products; except furniture	109	Jewellery and related articles; manufacture of musical instruments	169	Social work activities
50	Pulp	110	Sports goods; games and toys	170	Collection and treatment of sewage and liquid waste
51	Paper and paperboard	111	Miscellaneous manufacturing not elsewhere classified; recycling	171	Collection and treatment of solid and other waste (excl. waste incineration)
52	Articles of paper and paperboard (except paper stationary)	112	Recycling of metal waste and scrap	172	Waste incineration
53	Paper stationary	113	Recycling of non-metal waste	173	Sanitation; remediation and similar activities
54	Paper-based publishing; printing and reproduction	114	Electricity production - gas	174	Activities of membership organisations
55	Non paper-based publishing and reproduction of recorded media	115	Electricity production - coal	175	Recreational and cultural activities
56	Coke oven products	116	Electricity production - nuclear	176	Sporting and other activities
57	Refined petroleum products	117	Electricity production - oil	177	Dry cleaning; hair dressing; funeral parlours and other service activities
58	Processing of nuclear fuel	118	Electricity production - renewables (and other)	178	Private households as employers of domestic staff
59	Industrial gases	119	Gas distribution		
60	Dyes and pigments	120	Steam and hot water supply		

Appendix 2: Whole economy aggregated into market segments

Market Segment	Sectors No.	18 Aggregated Sectors
A	1-7	Agriculture
B	8-9	Forestry
C	10-12	Fishing
D	13-18	Mining
E	19-38	Food
F	39-48	Textiles
G	49-55	Wood & Paper
H	56-58	Fuels
I	59-70	Chemicals
J	71-79	Minerals
K	80-88	Metals
L	89-113	Equipment
M	114-121	Utilities
N	122-124	Construction
O	125-131	Trade
P	132-145	Transport & Communication
Q	146-177	Business Services
R	178	Personal Services

Benchmarking Carbon Emissions Performance in Supply Chains

List of Figures

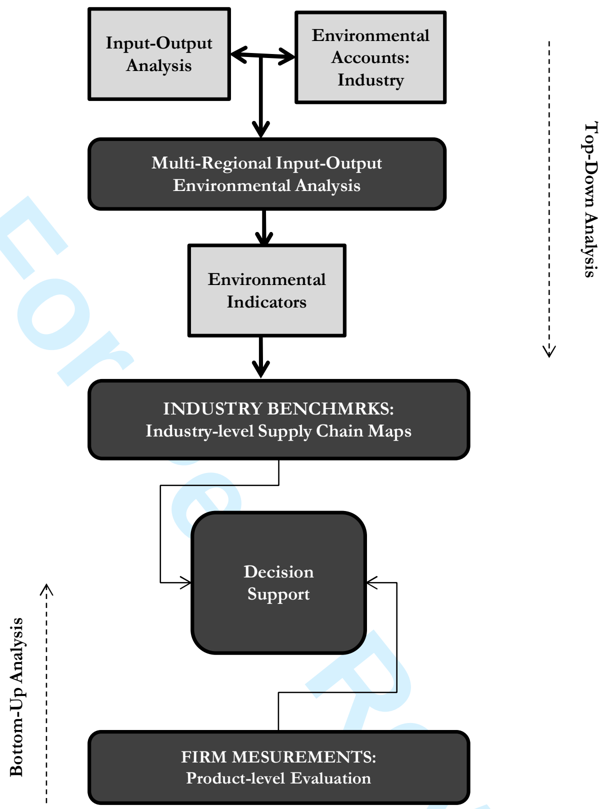


Figure 1: General overview of supply chain industry-level benchmarking framework

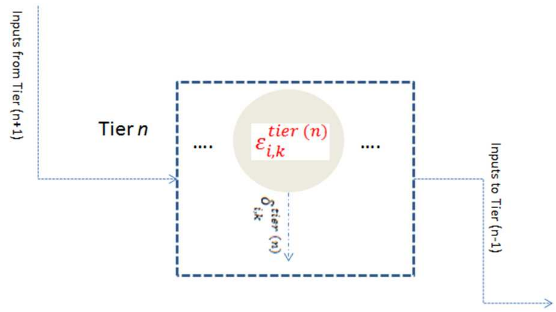


Figure 2: Supply Chain Map prototype

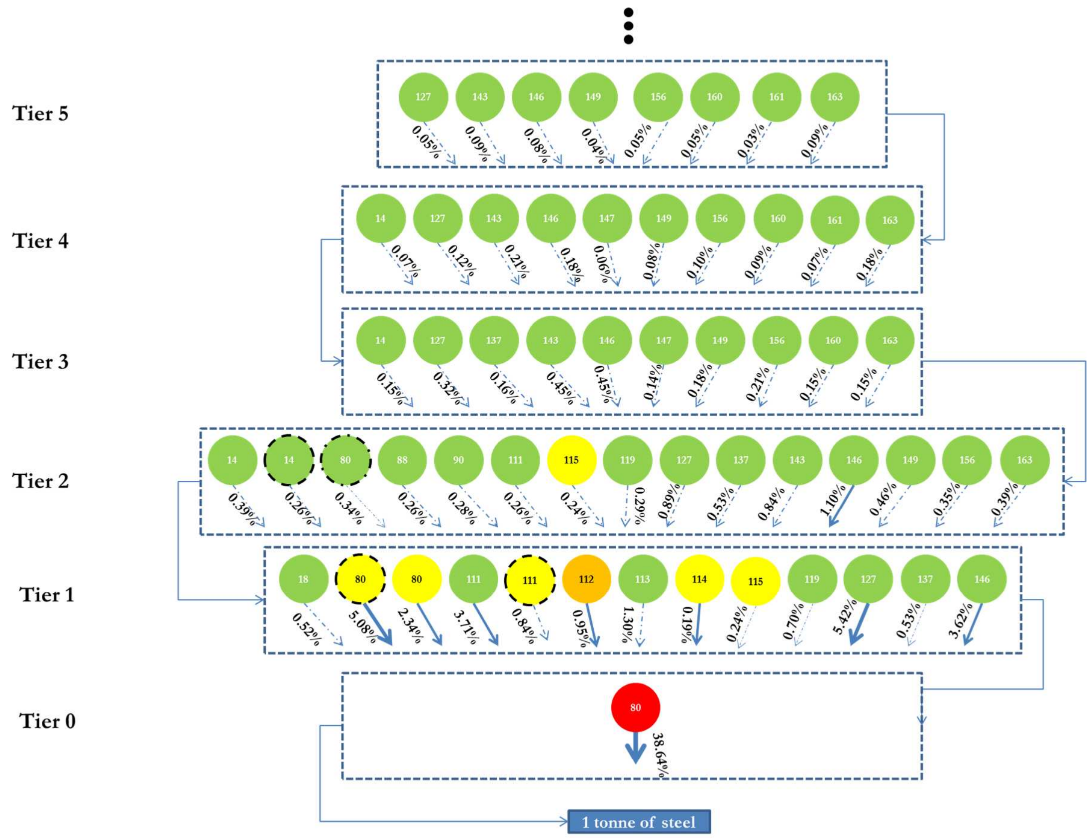


Figure 3: Industry-level Supply Chain Map representing average 1 tonne UK production of steel

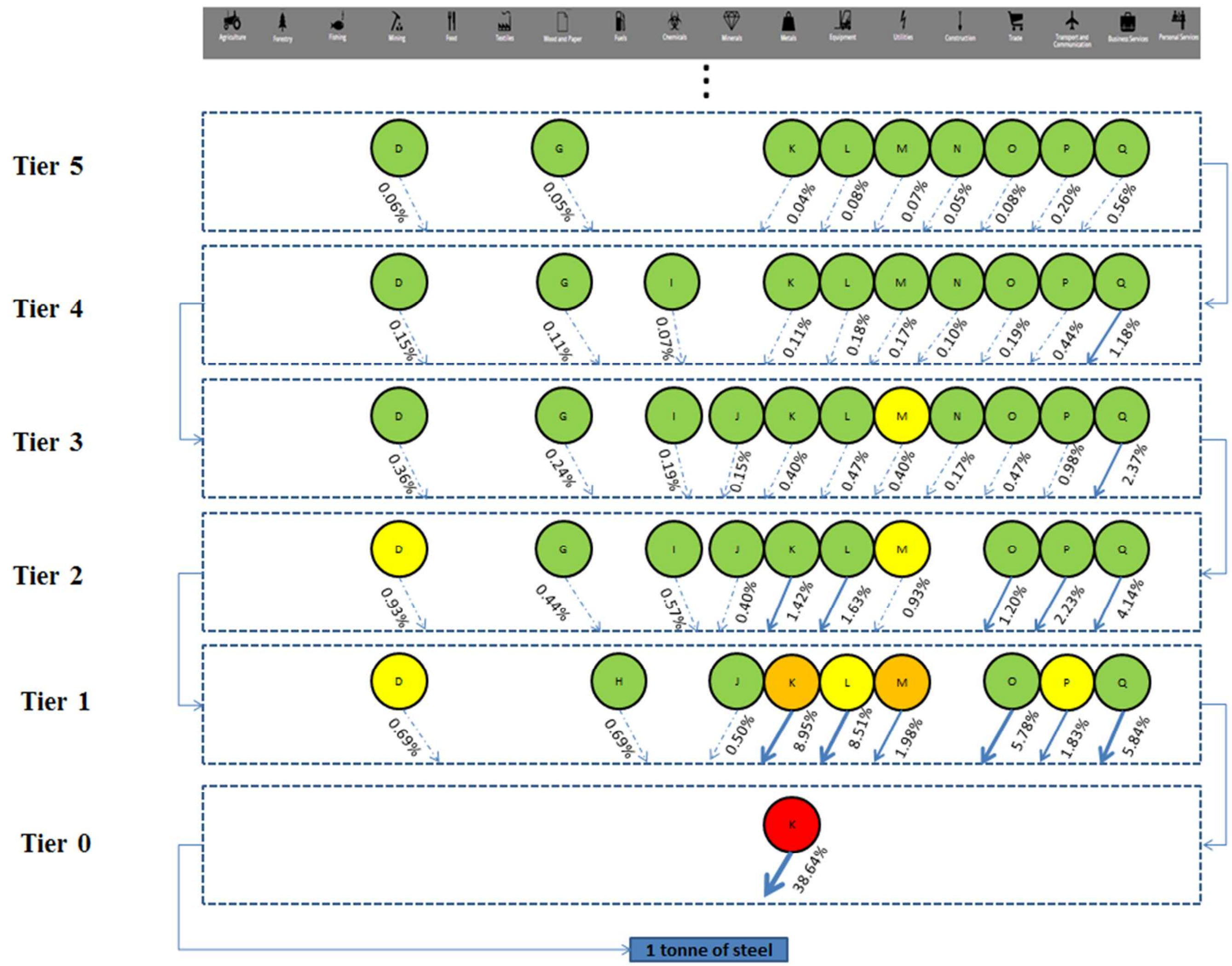


Figure 4: Aggregated Supply Chain Map

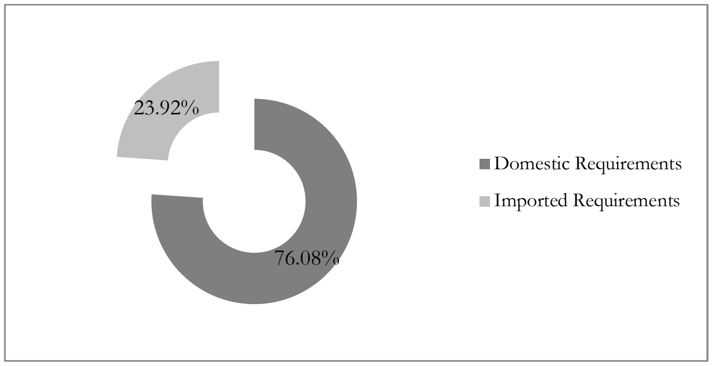


Figure 5: Split between domestic and imports resource requirements

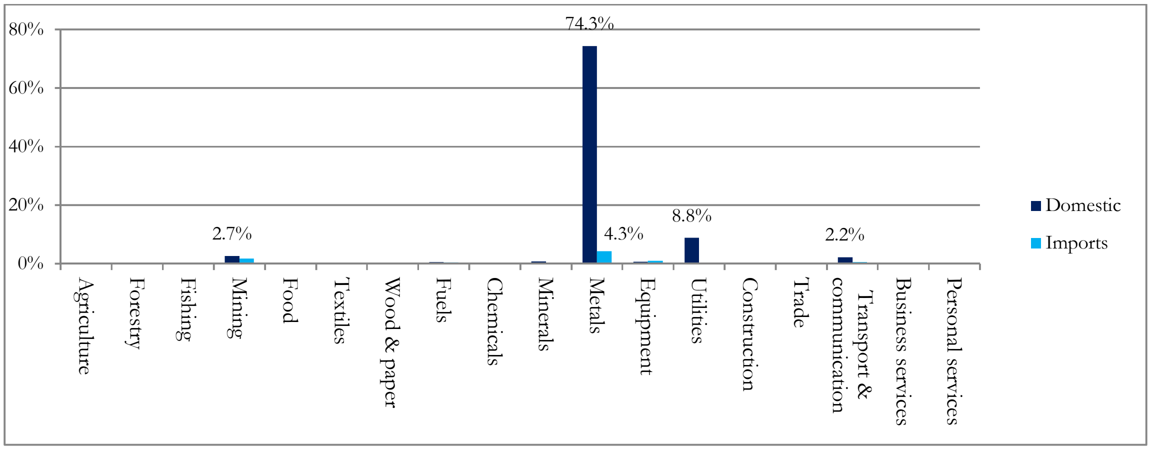


Figure 6: Supply chain carbon emissions classified by sector group

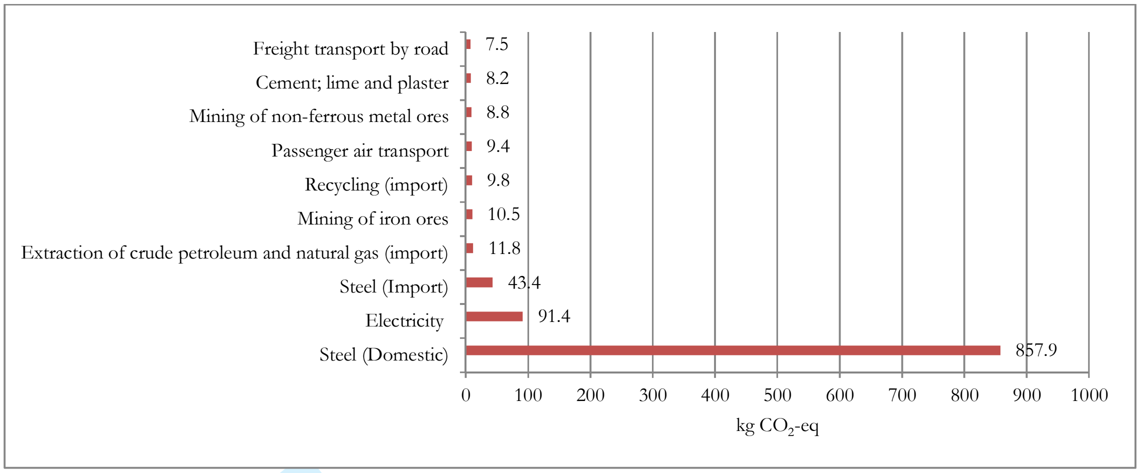


Figure 7: Detailed Supply chain carbon emissions by sector

Benchmarking Carbon Emissions Performance in Supply Chains

List of Tables

Table 1: Thresholds for sector selections based on input relevance at each supply chain tier

Tier	Selection Threshold
Tier 0	$\delta_{i,k}^{tier\,(0)} \geq 1.000\%$
Tier 1	$\delta_{i,k}^{tier\,(1)} \geq 0.500\%$
Tier 2	$\delta_{i,k}^{tier\,(2)} \geq 0.250\%$
Tier 3	$\delta_{i,k}^{tier\,(3)} \geq 0.125\%$
Tier 4	$\delta_{i,k}^{tier\,(4)} \geq 0.062\%$
Tier 5	$\delta_{i,k}^{tier\,(5)} \geq 0.031\%$

Table 2: Thresholds for sector selection based on emission intensity at each supply chain tier

Tier	Selection Threshold
Tier (n)	$\varepsilon_{i,k}^{tier\ (n)} \geq 1.000\%$

Table 3: Thresholds for relative emissions intensity representation at each supply chain tier

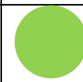
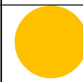
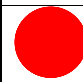
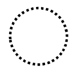
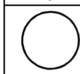
Impact	Interval	Symbol
Low	$\varepsilon_{i,k}^{tier\ (n)} \leq 1.00\%$	
Moderate	$1.00\% < \varepsilon_{i,k}^{tier\ (n)} \leq 5.00\%$	
High	$5.00\% < \varepsilon_{i,k}^{tier\ (n)} \leq 10.00\%$	
Very High	$\varepsilon_{i,k}^{tier\ (n)} \geq 10.00\%$	

Table 4: Thresholds for relative resource demand representation at each supply chain tier

Input	**Interval**	**Symbol**
Low	$\delta_{i,k}^{tier\ (n)} \leq 1.00\%$	⇢
Moderate	$1.00\% < \delta_{i,k}^{tier\ (n)} \leq 5.00\%$	→
High	$5.00\% < \delta_{i,k}^{tier\ (n)} \leq 10.00\%$	➜
Very High	$\delta_{i,k}^{tier\ (n)} \geq 10.00\%$	➡

Table 5: Differentiating between Domestic and Imported Supply Chain Input

Input	**Interval**
No line	*Domestic Input*
	*Imported Input*
	*Total Input*